Chapter 4
VLBI Tracking Observables

4.1 VLBI System Description

This section introduces the concept of VLBI tracking and examines major system elements. VLBI technology makes use of the broadband microwave radiation emitted by extragalactic radio sources such as quasars. The signals are typically very weak (< 1 Jy or 10^{-26} W Hz^{-1} m^{-2} of aperture); hence the need for relatively large antennas, low-noise receivers, and wideband recording devices. The DSN had an operational VLBI system for spacecraft tracking (referred to as the Narrow Channel Bandwidth [NCB] VLBI System [1,2]) from 1984 through 1998. The system operated at S-band and X-band on 34- and 70-m antennas. System temperatures were approximately 20 K at S-band and 30 K at X-band. The system recorded open loop at 500 kbit/s. The record rate of 500 kbit/s was chosen to facilitate near-real-time data transmission and processing for navigation support. This moderate data rate led to the descriptive system title “narrow,” in contrast with other radio astronomy systems, which operate at data rates of hundreds of megabits per second. Observables generated by the VLBI system are sometimes referred to as “instantaneous angles,” even though several minutes of integration time are typically necessary to reduce the error caused by system noise to a level comparable to other measurement errors.

Consider the situation in Fig. 4-1, where the wavefront from a distant source arrives as a plane wave at two widely separated antennas. The signals are amplified, heterodyned to baseband, digitized, time tagged and recorded. The recorded signals are subsequently cross-correlated to determine the difference in the signal time of arrival at the two stations. This differential arrival time is referred to as the VLBI delay and is composed of a geometric delay plus

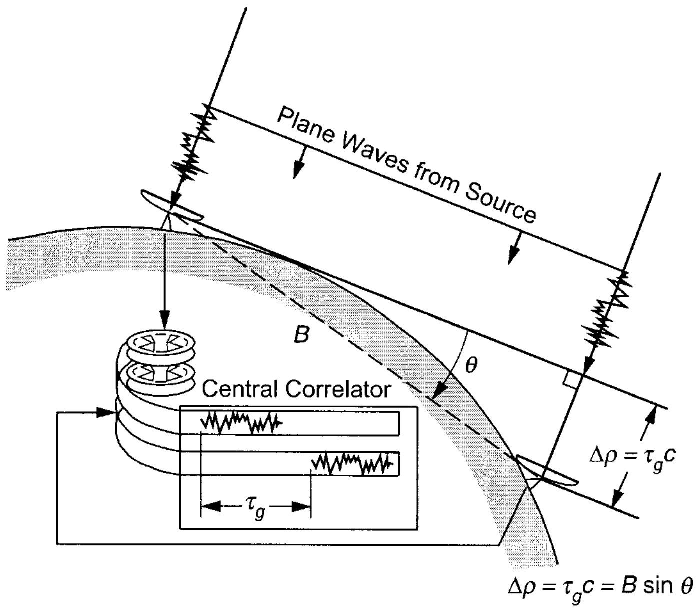

Fig. 4-1. Measuring angles with VLBI. Differential signal arrival time, τ_g, is obtained by cross-correlating signals recorded open loop at each end of the baseline.

delays due to station clock offsets and differences in signal delays through the ionosphere, troposphere, instrumentation, and so forth. The geometric delay can be expressed as

$$\tau_g = \frac{1}{c}\boldsymbol{B} \cdot \hat{s} \tag{4.1-1}$$

where $\boldsymbol{B}$ is the baseline vector between the two stations and $\hat{s}$ is the unit vector in the source direction. Thus, with a priori knowledge of the baseline length and orientation, one can infer from the geometric delay one angular component of the source position. The accuracy to which this angle can be measured depends not only on the precision of the VLBI delay measurement, but also on the accuracy to which the measurement can be calibrated for station clock offsets, differential instrumental and media delays, and baseline orientation errors.

Though the NCB VLBI system has now been retired, a modern system with improved capabilities is being implemented in 2000 and 2001. The new system is based on the Full Spectrum Recorder (FSR), which is used in the DSN for telemetry arraying and for open-loop radio science recordings [3–5], and is referred to as the VLBI Science Receiver (VSR). Data processing will be done by software, on a workstation. Computer speeds are adequate today so that narrow-bandwidth VLBI data may be correlated in a timely manner, without the need for special-purpose hardware.

4.1.1 Delta VLBI

One means for effectively reducing the contribution of uncalibrated errors in VLBI delay measurements is to introduce a second measurement, that of an angularly nearby source whose position is well known. Explicit differencing of observations from angularly nearby sources removes or substantially reduces the effects of common errors. For example, station clock offsets and instrumental group delays may be almost entirely cancelled. In this way, errors due to uncalibrated media effects and poorly modeled baseline vectors can be greatly reduced. The extent to which such errors are eliminated in the differential observable depends upon the commonality of the signal path, for example, how angularly close the sources are, the time offset between observations, and the degree to which the spectral characteristics of the signals are similar.

If one of the sources is a distant spacecraft and the other is a quasar, the spectral structures of the signals will differ significantly. Natural sources have broadband signals with nearly flat spectra spread over many gigahertz. Spacecraft signals, on the other hand, are band-limited (for example, 40 MHz at X-band), and contain a number of tones that are utilized for VLBI tracking. Open-loop recordings are made for each source, using frequency channels centered at the spacecraft tone frequencies. This is done so that instrumental effects will be as common as possible for the two sources. The recorded data are then transmitted from each station to a common workstation at JPL. At this point, the quasar signal phase is extracted by cross-correlation of the frequency channels between stations. The phase of each spacecraft tone is extracted by local model correlation, a process whereby the signal is mixed with a computer-generated model of the expected signal. Differencing tone phase between stations provides a measurement analogous to the cross-correlation phase for a quasar.

Measurements made from a single frequency channel yield phase delay to a fraction of a cycle. The total delay is ambiguous to λn, where n is an integer number of radio frequency (RF) cycles and λ is the wavelength. Multiple measurements of channels properly spaced in the frequency band enable the determination of unambiguous delay through a process referred to as bandwidth synthesis [6]. In this process, ambiguities are first resolved for the narrowest effective bandwidth, and then successively for wider bandwidths. After cycle ambiguities are resolved, delay is obtained as the slope of the phase versus frequency line. The unambiguous delay obtained from spacecraft measurements is referred to as differential one-way range (DOR), and the tones in the spacecraft spectrum from which the measurement is derived are referred to as DOR tones. The differential delay between spacecraft and quasar is termed ΔDOR, and yields a highly accurate measure of the spacecraft angular position in the radio source reference frame.

Ambiguous measurements of phase delays yield information only on the delay rate. This measurement type is important, however, since it may be obtained from spacecraft that emit only a carrier signal. Several hours of phase-delay-rate data may be used to infer angular coordinates in much the same way as Doppler measurements [7]. For a planetary orbiter, phase-delay-rate data directly measure the orientation of the orbit plane about the line of sight from Earth to the planet, as noted in Section 3.6.

4.1.2 Radio Source Reference Frame

One of the key characteristics of VLBI tracking technology is the development over the last two decades of a highly stable and accurate quasi-inertial reference frame with the associated catalog of approximately 200 source positions [8,9]. Source positions are determined in the ICRF with an internal consistency of better than 5 nrad [10]. This reference frame was adopted by the IAU in 1998 as the fundamental celestial reference frame, replacing the optical reference frame known as FK5. Among the by-products of the source catalog development are estimates of DSN baselines and improved models for precession and nutation [8,9,11]. Measured baseline lengths are consistent with plate tectonic models to about the 2-cm level. As noted in Section 3.3.4.1, Earth-fixed coordinates for most DSN stations have been determined to 3 cm or better in all components, using a combination of VLBI and other space geodetic techniques [12]. The newer sites have not yet been surveyed to this level.

A separate receiving system, which operates at a higher data rate than the NCB system, is used in the DSN to support the source catalog development effort. Data were acquired from 1978 to 1989 using the Mark II VLBI system [13], and since then using the Mark III VLBI system [14]. The installation of Mark III terminals operating at 112 Mbit/s, coupled with low-noise amplifiers having 400-MHz bandwidth and other improvements, have greatly increased the sensitivity of the system. These improvements continue to enable further advances in source position and baseline accuracies.

4.1.3 Radio and Planetary Frame Tie

Navigation to the planets using VLBI tracking requires knowledge of planetary ephemerides in the radio reference frame. The planetary ephemerides have evolved from many decades of observations, largely Earth-based optical and radar, supplemented with planetary encounter data and laser ranging to the moon [15]. Analyses of these data have produced lunar and planetary ephemerides in a self-consistent reference frame tied to the dynamical equinox and precessed to the epoch J2000 [16]. The most recent ephemerides are also fit to frame-tie data that directly align the planetary ephemeris with the ICRF [17,18]. The internal precision of the planetary ephemeris reference frame rivals that of the ICRF, at the 5-nrad level [19], but most individual bodies are not known to this level.

Within the planetary ephemeris frame, the positions of Venus, Mars, Earth, and the moon are all known to the 5-nrad level, due primarily to accurate measurements made over the last 30 years. Sources of these measurements include LLR, precise radio ranging to the Viking and Pathfinder landers, radar ranging to Venus, and ΔDOR measurements of the Magellan orbiter at Venus. The position of Mercury is known only to the 25-nrad level. Of the outer planets, Jupiter's position is best known at the 100-nrad level, due to ranging to the Voyager and Ulysses spacecraft, and ΔDOR measurements of the Ulysses and Galileo spacecraft [20,21]. The positions of the other large outer planets are known only to about the 250-nrad level, while the position of Pluto is uncertain at the microradian level [22,23].

The remaining uncertainty in the orientation of the planetary ephemeris frame with respect to the radio frame is at the 5-nrad level in all components [17]. This accuracy has only recently been achieved. The offset in the origin of right ascension was hundreds of nanoradians until the first VLBI measurements were made of spacecraft at planetary encounters. The Mars Viking and the Pioneer Venus orbiters provided an early opportunity for measuring the planetary-radio frame offset. The position of each orbiter relative to the planet was determined from Earth-based Doppler tracking. Delta VLBI phase-delay-rate measurements between the orbiter and an angularly nearby radio source then provided a measure of the frame tie. Accuracies of about 100 nrad in both right ascension and declination were achieved [24]. Experiments to refine the frame tie included measurements of millisecond pulsars and the timing of occultations of radio sources by planetary objects. But the first significant improvement in knowledge of the frame tie was made in the early 1990s by comparing the terrestrial reference frames associated with VLBI and LLR data analyses. The VLBI solutions tie the DSN stations to the radio frame, while the LLR solutions are closely tied to the planetary ephemeris reference frame [16]. The tie between the DSN and the LLR stations is determined from common site measurements made by the NASA Crustal Dynamics Project, using VLBI and SLR. The frame tie was determined by this method to 15 nrad in each component [25]. This accuracy was confirmed and improved to the 5-nrad level by the acquisition of 18 ΔDOR measurements of the Magellan orbiter at Venus between 1990 and 1994 [17,26].

4.1.4 VLBI Calibration System

While the ΔVLBI system is largely self-calibrating, a number of errors do not totally cancel when measurements to individual sources are differenced.

For example, the cancellation of errors due to PM, UT, station locations, and media delays is dependent upon the angular distance between sources. In order to minimize these effects in the tracking observable, it is necessary to select radio sources angularly close to the spacecraft and apply the most accurate available calibrations for these effects. Previously, the NCB VLBI system itself provided the DSN with accurate means for timely determination of UT, PM, and clock parameters. The GPS calibration system, anchored by monthly wide-band VLBI measurements, is now used for this purpose. The GPS calibration system is also used to generate line-of-sight calibrations for ionospheric delays and calibrations for zenith tropospheric delays (see Chapter 3).

4.1.5 Major Error Sources

The major sources of error in present day ΔVLBI observations are typically measurement signal-to-noise ratios (SNRs), uncalibrated troposphere delays, baseline errors, and instrumental delays (see Fig. 4-2). Models for estimating these measurement errors have been developed [27]. This section summarizes the major system design and calibration limitations to overall performance. Expectations for future system improvements are presented in Chapter 5.

The magnitude of each error source in VLBI is highly dependent upon system operating parameters. For example, SNR for quasar measurements depends upon quasar flux density, recording bandwidth, system temperature, antenna diameter and efficiency, and integration time. Although trade-offs may be made between such variables as antenna size, source strength, and integration time, they may be constrained by other considerations, such as the availability of sufficiently strong sources angularly close to the spacecraft. Ideally, one would like to find strong (1-Jy) sources within a few degrees of the spacecraft, but this situation is more the exception than the rule.

Consider the map of available sources for VLBI tracking of the Galileo spacecraft, shown in Fig. 4-3. Catalog sources within a 15-deg band about the Galileo trajectory vary in strength from 1 Jy down to 0.1 Jy. It should be noted that the scarcity of known sources near the encounter coordinates is due to the intersection of the ecliptic and galactic planes. The direction specified by 18-h right ascension and –23-deg declination is in the plane of the Milky Way, directly toward the galactic center. The large quantity of radio emissions originating within our own galaxy has hampered efforts to survey and catalog compact extragalactic radio sources in this direction. For ΔDOR measurements, a source strength of 0.4 Jy was required using a 70-m and 34-m DSN antenna pair with the now-retired NCB VLBI system and a 10-min integration time. The new VSR design has the capability to support a higher data recording rate that will lower the source detection threshold by a factor of two or more. This increased sensitivity will allow the selection of a weaker source angularly closer to the spacecraft, or the use of smaller antennas.

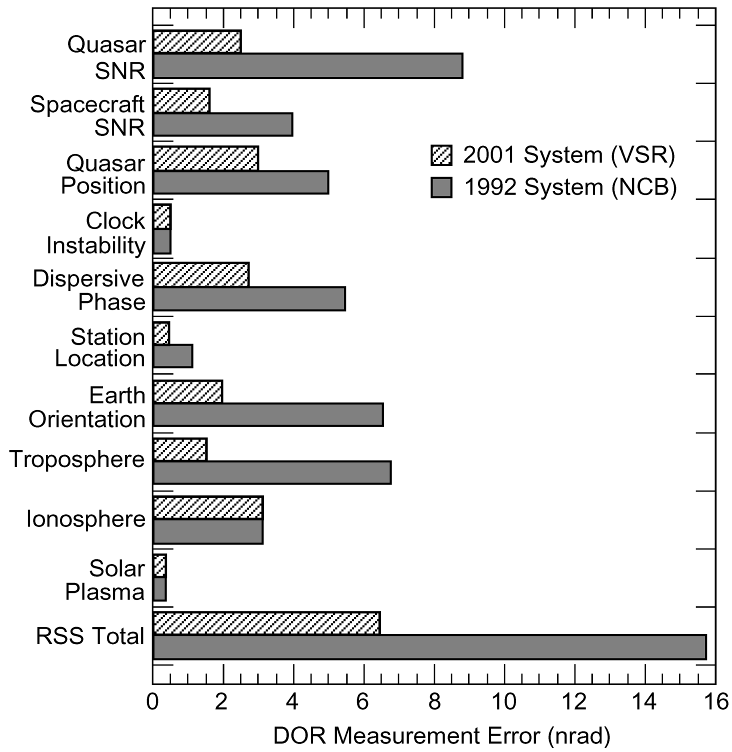

Fig. 4-2. Error budget for spacecraft-quasar ΔDOR delay measurements for both the prior- and next-generation tracking systems, consistent with system characteristics given in Table 4-1.

While most errors scale down with angular separation between the spacecraft and the quasar, instrumental errors depend more on the characteristics of the radio signals. In particular, dispersive instrumental effects in ΔDOR measurements are inversely proportional to the total spanned bandwidth of the recorded signals. Limitations on spanned bandwidth are typically imposed by the spacecraft radio design; the quasars are sufficiently broadband. Moreover, the DSN front end can accommodate 400 MHz at X-band and 100 MHz at S-band. On the other hand, for all spacecraft currently in flight at the time of publication, the widest DOR tone spacing is 38 MHz at X-band. International frequency allocations limit spacecraft transmissions to 50 MHz at X-band. However, the allocated bandwidth at Ka-band is 500 MHz [28]. Future ΔDOR systems, operating at Ka-band and utilizing tones separated by 200 MHz, will greatly reduce instrumental and other dispersive errors.

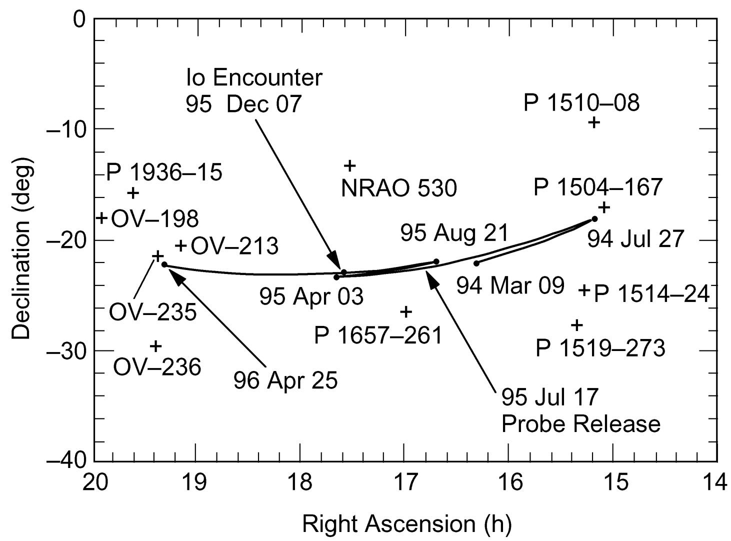

Fig. 4-3. Angular components of Galileo spacecraft trajectory during the Jupiter approach. Also shown are catalog radio sources within 15 deg of the trajectory and having flux greater than 0.1 Jy.

4.2 Spacecraft VLBI System Performance

Interferometric measurements directly determine angular components of spacecraft state. The inclusion of ΔDOR data with long arcs of Doppler and range data desensitizes trajectory solutions to mismodeled dynamic forces, and can improve knowledge of spacecraft position by a factor of five or more. The realized improvement in trajectory accuracy with respect to a target depends on knowledge of the target position in the radio frame. Both the Galileo and Mars Observer projects had a requirement for ΔDOR measurements with a one-sigma accuracy of 50 nrad during their interplanetary cruise phases. Requirements to deliver landers to the surface of Mars are expected to be in the range of 5 to 10 nrad.

The contribution of individual error sources to the overall measurement accuracy is known as the error budget. An error budget for ΔDOR measurements is shown in Fig. 4-2. The estimate labeled "1992" assumes a spacecraft DOR tone spacing of 38 MHz at X-band along with use of the NCB system, and hence applies to both Galileo and Mars Observer. The performance of the NCB VLBI system on Galileo and Mars Observer was balanced in that errors due to thermal noise, station instrumentation, platform parameters, and media delays were comparable in size. Measurement errors were estimated using the formulations in [27]. See Table 3-3 for assumptions on calibration system accuracies. See Table 4-1 for assumptions on receiving system characteristics and observation geometry. As shown in Fig. 4-2, the typical accuracy of the ΔDOR system in 1992 was 16 nrad. However, some items in the error budget depend strongly on geometry. With other assumptions fixed as in Tables 3-3 and 4-1, measurement accuracy of 50 nrad was possible for even the most unfavorable geometries involving spacecraft in the ecliptic observed from DSN baselines. In the final analysis, the performance of the NCB system was adequate to meet navigation requirements of the Galileo and Mars Observer missions.

Interferometric measurements have also been made of several spacecraft not equipped with DOR tones. Differential one-way range measurements were acquired by using harmonics of a spacecraft telemetry subcarrier signal. This technique was employed to enhance cruise navigation for the Voyager [29], Magellan [30], and Ulysses [20] spacecraft. However, for these spacecraft, the widest spacing of detectable telemetry signals was somewhat less than the 38 MHz provided by the DOR tones of Galileo and Mars Observer. Specifi-

Table 4-1. Spacecraft-to-quasar ΔDOR assumed characteristics.

Characteristics	Assumed Value	
Spacecraft observing time	10 min	
Spacecraft-to-quasar angular separation	10 deg	
Minimum elevation angle	15 deg	
Elevation angle difference	5 deg	
Quasar flux	0.4 Jy	
Observing band	X-band	
Spanned bandwidth	38.25 MHz	
System noise temperature	30 K	
	VLBI 1992	VLBI 2001
Quasar coordinates	5 nrad	3 nrad
Quasar observing time	10 min	20 min
Radio and planetary frame tie	25 nrad	5 nrad
DSN antennas	70m and 34m	34m and 34m
Channel bandwidth	0.25 MHz	1 MHz
Channel recording	multiplexed	parallel
Phase dispersion	1 deg	0.5 deg

cally, the maximum usable tone spacings for Voyager, Magellan, and Ulysses at X-band were, respectively, 14 MHz, 31 MHz, and 6 MHz. Since system noise and phase-dispersion errors scaled inversely with maximum tone spacing, these components of the error budget were increased by a corresponding amount from the 1992 level shown in Fig. 4-2.

Figure 4-4 displays Magellan ΔDOR residuals acquired early in cruise. The residuals are shown for two trajectories. The white symbols represent the ΔDOR pass-through residuals relative to a trajectory determined from Doppler data spanning the time interval shown in the figure. The black symbols are the ΔDOR residuals to a trajectory fit to both the Doppler and the ΔDOR data (weighted at 50 nrad). Note that the Goldstone-to-Madrid baseline is oriented nearly east-west, so that measurements on this baseline are sensitive to spacecraft right ascension, whereas measurements on the canted Goldstone-to-Canberra baseline are equally sensitive to right ascension and declination. Comparison of the ΔDOR residuals for the Goldstone-to-Madrid baseline from the two solutions shows that the Doppler-only solution does a good job of determining right ascension, although a small drift over the 17-d data arc is apparent. Since right ascension has been determined fairly well, large ΔDOR residuals for the Goldstone-to-Canberra baseline must be attributed to a trajectory error in the declination component. Comparison of these residuals for the two solutions shows that the spacecraft declination determined from Doppler alone is biased by at least 2.3 μrad and drifts by 1.6 μrad over the 17-d data arc. When the ΔDOR data are fit, residuals for both baselines are reduced to the

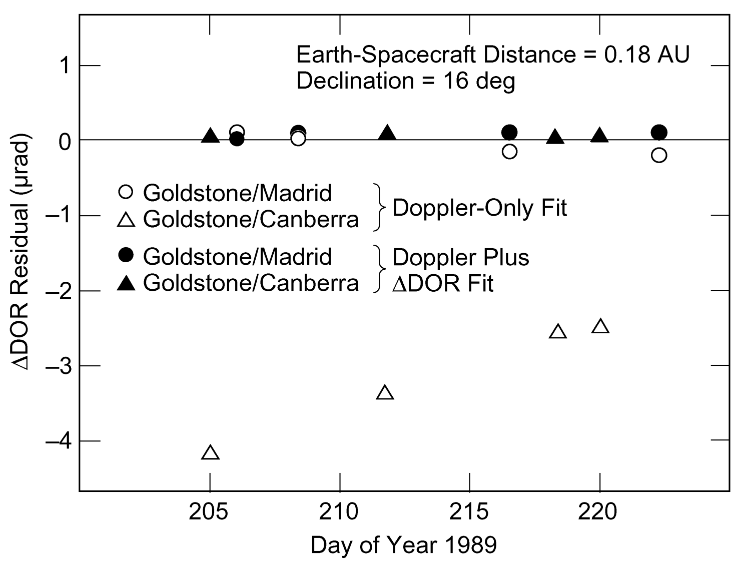

Fig. 4-4. Magellan ΔDOR residuals for two estimated trajectory solutions.

level of the data accuracy, which is 50 nrad. For this case, an improvement of a factor of 46 in solution accuracy was achieved.

The inaccuracy of the Doppler-only solution was due primarily to mismodeled solar pressure accelerations. The effect of the mismodeling was to move the spacecraft position estimate in the direction least well determined by Doppler; that is declination. The ΔDOR data exposed the modeling problem. Further, these data directly measured each angular component, and hence produced an accurate solution even in the presence of mismodeled accelerations. The two solutions illustrated in Fig. 4-4 were interim solutions developed for the purpose of data evaluation.

A similar modeling problem with small forces contributed to the loss of the Mars Climate Orbiter in 1999. A trajectory error accumulated in the declination direction, resulting in inconsistencies in solutions obtained from different data processing strategies. These inconsistencies were not resolved to identify the actual error. Unfortunately, no angular data types were employed as a check against this type of problem. Several reviews were conducted afterwards. In the *Report on Project Management in NASA,* by the Mars Climate Orbiter Mishap Investigation Board [31], one of the "lessons learned" in the section on systems engineering states:

> Develop and deploy alternative navigational schemes to single-vehicle, Deep Space Network tracking for future planetary missions. For example, utilizing "relative navigation" when in the vicinity of another planet is promising.

The planned implementation of a robust, next-generation ΔDOR capability addresses this point.

4.3 Utility of Open-Loop Recordings

Open-loop recordings of radio sources, as is done in VLBI, can be made even if one does not have good a priori knowledge of source position or signal frequency. With open-loop recordings, in the event that the signal is weaker than expected, less stable, or off in frequency, extra effort can be applied during signal processing to generate observables. By contrast, systems that rely on real-time signal detection may fail under these conditions.

Open-loop recordings were used in a scientific investigation during the entry of the Galileo probe into the Jovian atmosphere. The prime radio link during descent was a transmission from the probe to the Galileo orbiter that was flying overhead. The orbiter used a closed-loop radio system to track the probe signal in real time. These Doppler measurements provided a one-dimensional profile of the atmospheric winds. At the same time, open-loop recordings were made of the probe signal at two radio telescope observatories on Earth. Even though the signal received on Earth was a billion times weaker than the prime radio link due to the propagation direction being off the probe antenna boresite and the significantly larger distance to the probe, the signal was successfully detected in nonreal time and provided a valuable second profile of wind velocity in the Jovian atmosphere [32].

Open-loop recordings and subsequent specialized signal processing were used in 1999 to verify approach navigation for the Mars Polar Lander (MPL) [33,34] and to search for the signal that might have been transmitted by MPL from the surface of Mars [35]. Another use of open-loop techniques (under special circumstances) could be in situ tracking between orbiters at Mars. Analyses of these open-loop recordings, after transmission to Earth, could, if necessary, provide additional information beyond that of onboard closed-loop systems.

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